Numerical and experimental comparison of the performance of SDHW and PV-SDHW systems

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Abstract

In this paper, various configurations of PV assisted Solar Domestic Hot Water (SDHW) systems using different pump are evaluated numerically and experimentally. A detailed model of direct current (D.C) pump on considering a multi-physics modeling (thermal, hydraulic, electric and mechanic) has been developed in TRNSYS environment. Different electronic devices (Linear Current Booster, Maximum Power Point Tracker, special start-up control device) are also integrated in order to compare these different solutions of 'solar pump' proposed by manufacturers. The models of pump and electronic devices are validated thanks to the experimental set-up installed in the French National Institute for Solar Energy. The numerical data show a good agreement with the experimental results.

Keywords: *Photovoltaic, SDHW, solar pump, experimentation, model*

1. Introduction

The use of solar energy to heat water is very judicious because of its constant demand throughout the year. Currently, the design of solar domestic hot water (SDHW) system is well developed and the installations present well known performances. In standard SDHW systems, the fluid in the thermal solar collector circulates according to the temperature difference between the collector outlet and the bottom of storage tank. This control strategy leads to additional costs associated with the consumption of auxiliary energy (controller and pump) and the risk of dysfunction due to the temperature sensors [1, 2]. Using PV source to power the pumps in SDHW systems is an attractive concept as it permits to simplify the controller and no sensor is necessary. A number of researches have been realized on various aspects of the performance of PV pumping systems [3-5]. Different models of pump were developed for simulation works. However, most of models are based on the characteristics of a motor-pump combination [3, 4, 6]. In this way, it seems difficult to be used for analyzing the effects on pump's startup. Besides that, such models are always based on a specific motor and pump for a specific weather condition, which could not be used in different systems. Therefore, in our work, a TRNSYS [7] based simulation model of D.C pump was proposed. An experimental set-up has been installed at the center of National Institute for Solar Energy (INES). The experimental results permitted validating the numerical models in this system. Then the pump and electronic device models are used to evaluate the annual energy performance of PV-SDHW systems, and to compare with standard systems (On-Off system, matched flow rate systems with various temperature differences between the inlet and outlet of the solar collector).

2. Experimental study

2.1. Experimental set-up

An experimental set-up is established in the National Institute for Solar Energy (Fig.1). It consists of two serpentine flat-plate collectors (2 and 4 m²) connected in parallel, a storage tank of 400 liters with an internal coil heat exchanger emplaced in the bottom of the tank, A PV module of 20 Wc , two D.C pumps and the hydraulic piping system. The PT1000 2-wire temperature probes were used for all temperature measurements. The mass flow rate is recorded by an ultrasonic flowmeter. The solar irradiance received on the collector could be gathered from a meteorological station.

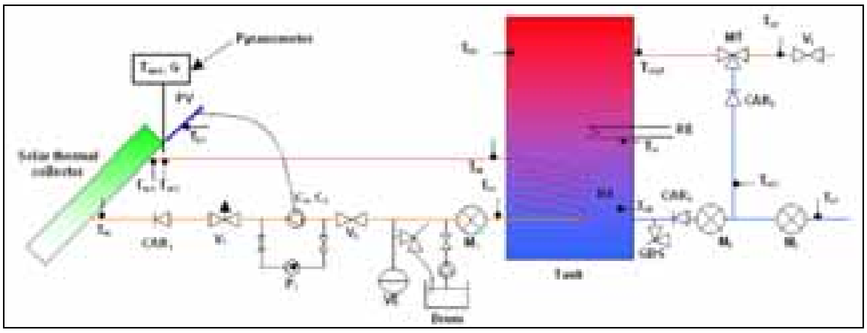

Fig. 1. Experimental set-up at INES

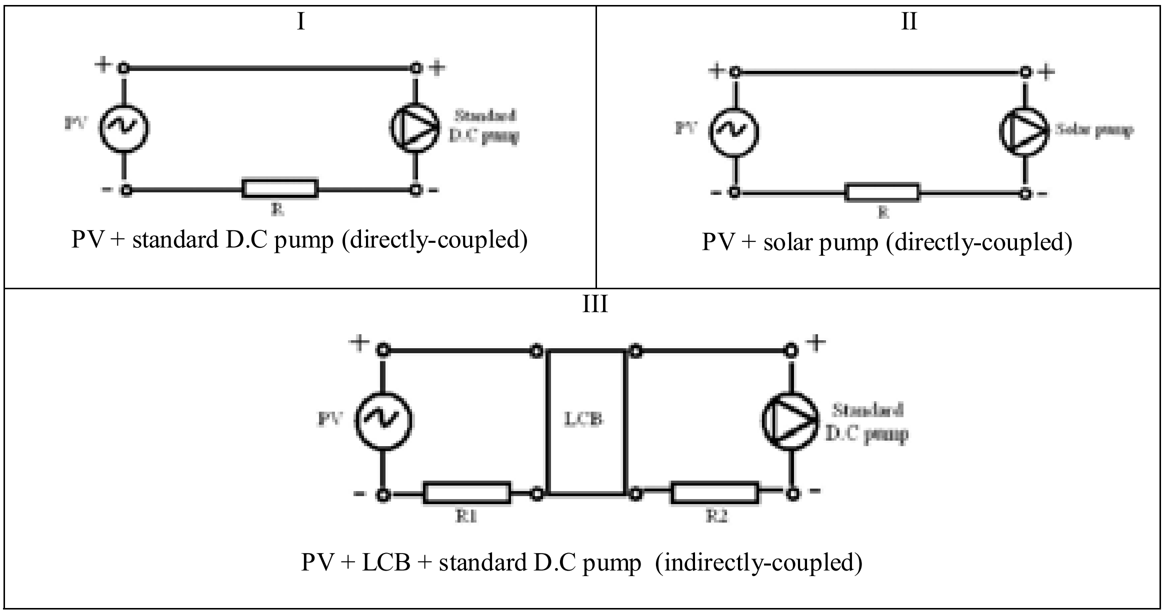

Fig. 2. Equivalent scheme of PV-pump sub-systems

Three configurations of PV-SDHW related to various pumps and modes of coupling (direct and indirect) were evaluated experimentally as shown in Fig.2. the resistances R, R1, R2 are used to determine the current in the circuits.

2.2 Results and discussion

According to the experimental results, the standard D.C pump begins running at a solar radiation of about 350 W/m². The solar pump integrating a capacitor and a MPPT (*Maximum Power Point Tracker*) allows boosting the pump start-up, which occurred at a lower radiation level (between 200 W/m² and 250 W/m²). The use of the LCB (*linear current booster*) can also improve the pump start-up performance (200 W/m² and 250 W/m²). However, the efficiency of standard D.C pump is just slightly lower than that of the solar pump and globally the efficiency of both these two pumps remains relatively low (max 14%) compared to the other AC pumps and high power D.C pumps.

The operating points of the solar pump are close to the maximum power points of PV module. For the other three configurations, the operating points are relatively distant from the point of optimum operation. The flow rate in solar pump is about 15 l/h.m² higher than that in standard D.C pump for the same level of solar radiation, which makes a direct consequence of reducing the fluid temperature at the outlet of solar thermal collector, and thus reduces heat losses thereby increasing the annual energy performance. Moreover, a significant difference of flow rate between the morning and afternoon (10 l/h.m²) is observed in both of these two pumps because of the change of the fluid viscosity. The temperature difference between inlet and outlet of the thermal collector (between 15 and 20 °C) is too high for both the standard D.C pump and solar pump (Fig.3).

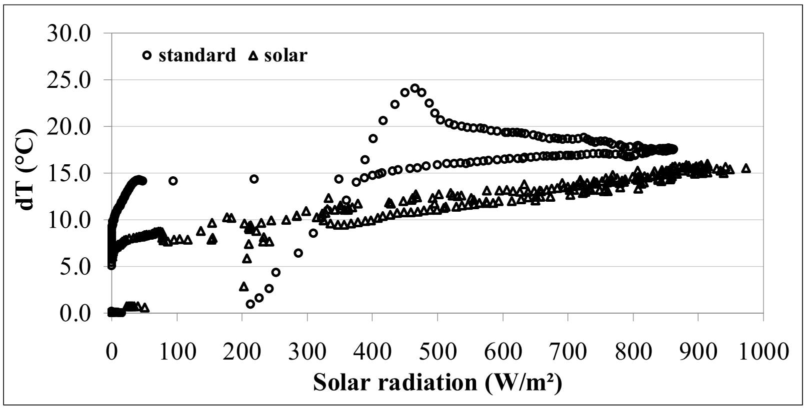

Fig. 3. Comparison of temperature difference between inlet and outlet of the thermal collector

Considering such significant temperature differences, we conducted a preliminary numerical evaluation of the annual energy performance of PV-SDHW systems using solar pump, which is the most efficient and then compared the results with conventional systems (on-off and matched flow rate systems). The solar pump flow rate is calculated based on the solar radiation ($Qcol = f(G)$) derived from experimental results. The results show that the matched flow rate system with a temperature difference of 5 °C across the thermal collector provides the lowest energy consumption, while the PV-SDHW system with solar pump consumes slightly more. However, the energy consumption of the controller and the pump is zero in the case of PV-SDHW systems. Finally, despite a non-optimized design as the temperature difference between input and output of the collector is relatively high, the PV-SDHW system using solar pump presents the lowest overall consumption.

3. System modelling

3.1. Mathematical description

The PV generator considered in this study is a 36-cells mono-crystalline module. A 4-parameter model is proposed [8]. The *I-V* characteristic can be described as:

$$I = I_L - I_D = I_L - I_0 \left[\exp\left(\frac{V + IR_s}{A} \right) - 1 \right] \tag{1}$$

Where, I_L is the light current at the operation irradiance level; I_D is the diode current (A); Io is the reverse saturation current (A); I is the operation current (A); V is the operation voltage (V); R_s is the series resistance (Ω); A is the thermal voltage (V).

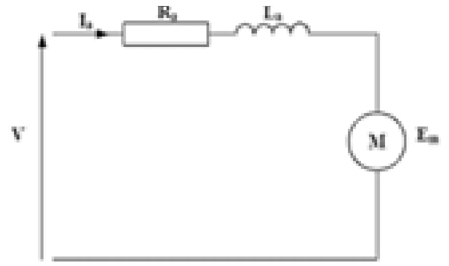

Fig. 4. Equivalent electric scheme of brushless D.C motor

The pump model is based on a standard direct current (D.C) pump. The model of the solar pump is then developed from the standard D.C pump model by integrating the standard model of the Maximum Power Point Tracker (MPPT). The model of the standard D.C pump is realized in two parts: brushless D.C motor and centrifugal pump in order to analyse the influence of the pump start-up characteristics. Within the framework of our study, the mathematical description of the model is carried out in three steps according to the real operation, which we highlighted during the tests (Fig.5).

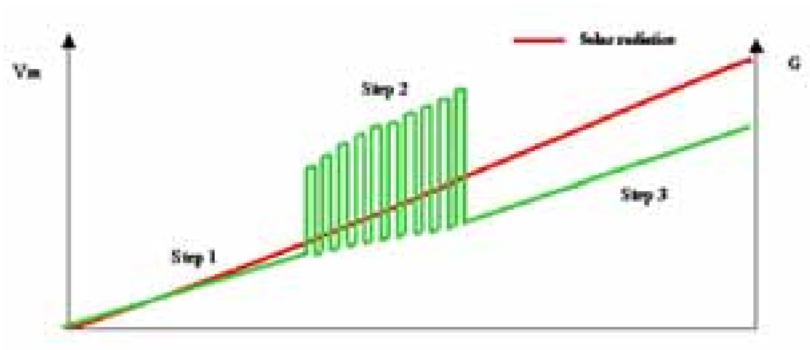

Fig. 5. Pump start-up steps

Step 1: The motor begins running. The variation of the motor current and voltage increase linearly with the solar radiation. The evolutions of the voltage and the current respect the **law of Ohm**. During this period, the levels of voltage and current are too low to run the motor. At the end of this step, the tension and the intensity are sufficient to start the electronic device of control.

Step 2: (**Transient electric regime**) When enough voltage and current is supplied to the pump, the electronic control device facilitating the motor start-up begins to work. The voltage and the current vary alternately. The motor run punctually. We suppose thus during this step, the rotation speed ω is zero and thereby the motor electromotor force and the pump load torque ($T_L=0$).

The motor voltage depends on the current and the electrical characteristics of motor such as the armature resistance and the motor inductance can be expressed as :

$$V_m = R_a I_a + L_a \frac{dI_a}{dt} \tag{2}$$

Where V_m is the applied motor voltage (V); I_a is the armature current (A); R_a is the armature resistance (Ω); L_a is the armature inductance (H).

Step 3: (**Permanent regime**) once the motor started, the voltage shut on the inductance is negligible compared to the force electromotor force E_m, which is much more higher. So we suppose that this period is in permanent mode, therefore

$$V_m = E_m + R_a I_a = K_v \omega + R_a I_a \tag{3}$$

Where, E_m is the motor electromotor force emf (V); K_v is the voltage constant; K_t is the torque constant; R_a the armature resistance; ω is the motor shaft speed (RPM);

The relation between the motor torque and the speed rotation becomes:

$$K_m I_a = A_1 + B_1\omega + A_2 + B_2\omega^{1.8} \tag{4}$$

Concerning the model of centrifugal pump, the flow rata is determined as a function of the pump head and the motor voltage, which presents by a regression polynomial.

$$\dot{m} = a + bH + cH^2 + dH^3 + eV_m + fV_m^2 + gV_m^3 + hHV_m + iHV_m^2 + jH^2V_m + kH^2V_m^2 \tag{5}$$

The models of the MPPT and LCB are developed in a simplified way.

3.2. Model validation

The model than was integrated in the TRNSYS environment as a type. Fig.6 shows the measured pump flow rate of the classic pump and solar pump together with the simulated flow rate as a function of the global solar irradiance. Under the same level of solar radiation, the flow rate of classic pump is much more lower which would induce the higher mean temperature of fluid in the solar collector and thereby more thermal losses. The significant difference (especially when solar radiation $G < 700$ W/m²) of the flow rate observed in the experimentation between the morning and afternoon is due to the viscosity change of the fluids related to the variation of fluid temperature. However, this point was not highlighted in most of the similar studies, which would reduce the performance of the global system. In the pump model, we have taken into account this influence of viscosity in the calculation of the coefficient of pressure drop in the solar loop. An equation incorporating viscosity is used to calculate the pump rotation speed, which is related to the pump head:

$$Q_{\_cap} = Q_{\_capsimu}\left(C_1 \upsilon_{cor} + C_2\right) \quad \text{[l/h]} \qquad (6)$$

With, C_1 and C_2, coefficients related to the viscosity, obtained experimentally. The simulated flow rate presents a good agreement with the experimental data as show in the figure.

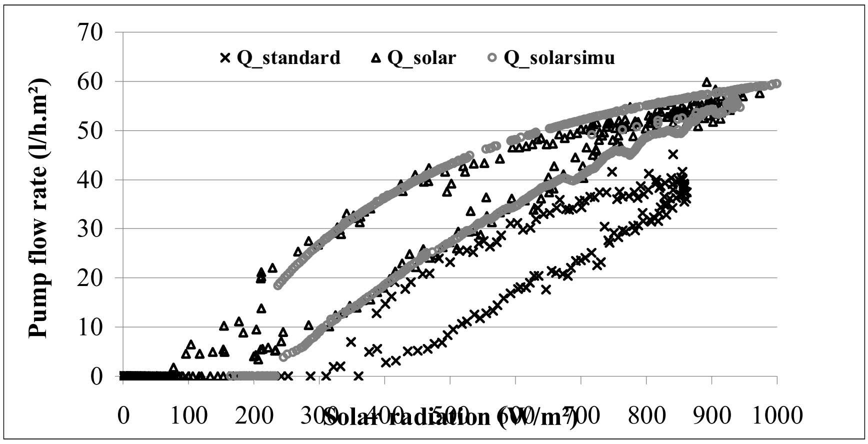

Fig. 6. Pump flow rate as a function of the solar radiation according to the different configurations

3.3. Evaluation of system performance

Then the pump and electronic device models are used to evaluate the annual energy performance of PV-SDHW systems using two different kind of pump, and to compare with standard systems (On-Off system, matched flow rate systems with various temperature differences between the inlet and outlet of the solar collector). As shown in Fig.7.

(1). ON-OFF with a flow rate of 50 l/(h.m²)

(2). Matched flow rate system with $\Delta T = 5$ °C (between inlet and outlet of solar thermal collector), Maximum flow rate 50 l/h.m²

(3). Matched flow rate system with $\Delta T = 9$ °C, Maximum flow rate 50 l/h.m²

(4). Matched flow rate system with $\Delta T = 13$ °C, Maximum flow rate 50 l/h.m²

(5). Matched flow rate system with $\Delta T = 17$ °C, Maximum flow rate 50 l/h.m²

(6). PV-SDHW: directly coupled PV - standard D.C pump

(7). PV-SDHW: directly coupled PV - solar pump

The following hypothesis are considered in our simulation work:

Weather condition: Lyon-satolas

Solar thermal collector surface: 6 m²

Tank volume: 400 l

Hot water consumption: 200 l/jour

Cold water temperature: monthly value used in RT2005

Auxiliary heater in the tank: 3 kW

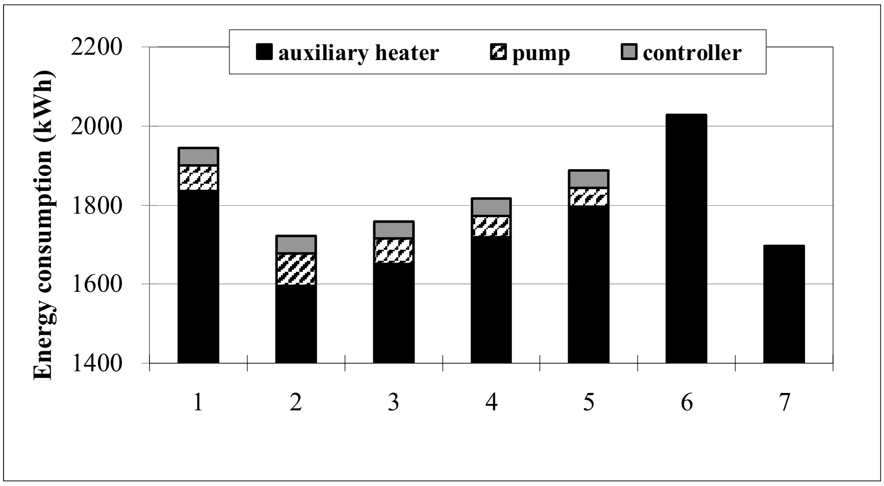

Fig. 7. Comparison of energy consumption of different SDHW systems

The matched flow rate system with ΔT = 5 °C presents the lowest energy consumption on the auxiliary heater. However, in the PV-SDHW systems, the annual consumption of auxiliary energy (pump and regulator) is deleted by coupling photovoltaic and represents approximately 100 kWh, so considering the global energy consumption, the system PV-SDHW system using a solar pump is the most favourite.

4. Conclusion

A PV-SDHW system using different type of pump has been studied experimentally and numerically by developing a new model of pump. The experimental results showed that the solar pump is the most efficient, although its design is not optimal (low efficiency of the pump, low flow rate leading to a high temperature of the thermal collector). In addition, it is also necessary to take into account the correct phase and behaviour of pump start-up procedure and the flow rate difference between morning and afternoon, to properly evaluate the energy performance through simulation. A model of the pump has been developed by considering the three steps of start-up period, and integrating the models of electronic devices such as MPPT and LCB. The results from simulations agree well with experimental values. The model represents correctly the temperature difference between morning and afternoon by taking into account the effect of viscosity. Regarding the annual energy performance, the system PV-SDHW with a solar pump is more interesting than traditional systems (on-off, matched flow rate systems) and other configurations of PV assisted SDHW systems.

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